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Concurrent Value-Driven Decision-Making Process for the Aircraft, Supply Chain and Manufacturing Systems Design

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Abstract: The integration of product design and supply-chain management can lead to an increase in the profitability and efficiency of companies. However, considering manufacturing, supply chain, and aircraft criteria in the early design phase increases the size of the solutions' trade space and, thus, the complexity of performing the decision-making process. This paper demonstrates how to leverage value-model theory to simplify the decision-making process when multiple criteria related to multiple systems are considered at the same time. The proposed concurrent approach is formalized from a systems-engineering perspective, considering the interactions between the lifecycle stages of the System of Interest, i.e., the aircraft, and Enabling Systems like the supply chain and manufacturing. A value-based interactive dashboard, called VALORISE, is developed to automatize the process, support decision-makers in modeling their expectations, analyze real-time strategic scenarios, and easily explore the value-driven trade space for best-solution identification. An aeronautical application case highlights the advantages of leveraging the proposed concurrent approach to overcome the limits of traditional approaches, in which decisions about supply chain and manufacturing are addressed once the aircraft configuration is decided.

Keywords: decision-making; value engineering; supply-chain management; aircraft design; manufacturing; system of interest; enabling systems; concurrent engineering; model-based systems engineering (MBSE); multidisciplinary design and optimization (MDO)

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1. Introduction

To meet heterogeneous societal needs, even more complex, innovative, sustainable, and circular aeronautical systems are required. The objective of sustainable and circular aviation is to reduce its environmental impact in terms of fuel consumption, waste, and emissions associated with all the lifecycle stages of the aeronautical system [1]. Hence, there is a necessity to extend the branches of aeronautical research to the entire aircraft lifecycle, from design to production to disposal after the end of system operability. This enlarges the design space, making the decision-making process even more complicated. However, it offers potential for aeronautical industries to succeed in a global and competitive market [2,3].

In this context, the Digital Development Process Group of the DLR Institute of System Architecture in Aeronautics aims to develop methods, processes, and tools that support the concurrent design of multiple systems to achieve solutions optimizing, at the same time, the System of Interest (SoI) and the Enabling Systems (ESs). In this study, the System of Interest is the aeronautical system; Enabling Systems, supporting the System of Interest in one or more lifecycle stages [4], are the supply chain and manufacturing systems. The supply-chain system is defined as a combination of multiple enterprises spread all over the world with the competencies to produce the aeronautical system. The manufacturing system, by contrast, is identified as the combination of machines needed to perform the manufacturing and assembly processes necessary for different aircraft components. Both the supply chain and manufacturing systems support the System of Interest in the development lifecycle stage in which the aeronautical system is built. Consequently, decisions on the supply chain and manufacturing have traditionally only been addressed once the aircraft configuration is fixed, therefore once decisions in terms of the operational performance of the aircraft have already been made [5]. This approach, however, limits the identification of the best solution in terms of competitiveness, sustainability, and circularity. Indeed, the most efficient aeronautical system is identified with the traditional approach. However, there is a high risk that this solution does not match, for instance, stringent environmental requirements (in terms of pollution emission) or production constraints (in terms of feasibility of realizing the product). This may lead to an unforeseen redesign of the aircraft with a consequent increase in cost [4,6].

Therefore, the challenge is to formalize, model, and automatize the existing complex interconnections between the System of Interest and Enabling Systems at the beginning of the System of Interest lifecycle, particularly during the concept stage, before the production of the system starts. The strength and innovation of this paper is, therefore, the consideration of the concept stage of the aircraft and the operational requirements, as is usually given, but also requirements related to the Enabling Systems, i.e., the supply chain and manufacturing systems. These requirements, often described in the literature as "nonfunctional requirements" [7], "-ilities" (e.g., manufacturability), or "-ities" (integrity) of the System of Interest [8], represent hidden sources of cost increase, especially in the case of large-volume production [9–11]. Trading in early-lifecycle-stage criteria derived from supply chain and manufacturing requirements at the same time as product (aircraft) criteria derived from operational requirements avoids re-work, reduces risk, and generally increases the value of the system [12,13]. Indeed, in recent decades, effort has been focused on the research of concurrent methodologies simultaneously accounting for criteria related to the product and/or supply and/or manufacturing [14–16] in the aeronautical context [17,18]. Most of these methodologies leverage value models to identify the best possible outcome when considering multiple and different criteria that are important for decision-makers. These methodologies, collected under the VDD (value-driven design) term [19,20], range from trade-space exploration [21–23] to value-centric design [24] and value-driven optimization [25,26]. They are based on different value models, with each having a unique interpretation, quantification, and representation of the term value. Among others, the most-used value-model theories are Net Present Value (NPV), Surplus Value (SV), Cost–Benefit Analysis (CBA), and Multi-Attribute Utility Theory (MAUT). In the first three value models, the value function represents the discounted cash flows generated over time and, thus, the profits gained from investing in a specific design of the system [25,27,28]. MAUT, by contrast, uses utility curves of system attributes to aggregate monetary and non-monetary stakeholder perceived value to obtain a ranked ordering of system design alternatives [29]. In general, the application of VDD methodologies leads to better solutions since they support the elicitation of such "-ilities", allowing the performance of tradeoff studies accounting for multiple stakeholders' needs and improving the communication between businesses and engineers [30].

This paper leverages MAUT to trade operational aircraft criteria with those derived from requirements related to manufacturing and supply-chain systems. In contrast to papers found in the literature, the methodology aims to include the requirements of Enabling Systems in the System of Interest concept lifecycle stage. In this way, stakeholders, needs, and requirements related to manufacturing and supply-chain systems are also accounted since the early lifecycle stages. Consequently, the best solutions can be identified for decision-makers' trading expectations related to aircraft production. The methodology is also applied in the aeronautical context for the identification of the best supply chain to produce a specific aircraft component.

Details of the formulation and implementation of the proposed concurrent value-driven decision-making process are introduced in Section 2. The results of the aeronautical application case are presented in Section 3, and in Section 4, the implications and the findings of this research activity are discussed. Finally, conclusions are reported in Section 5.

2. The Concurrent Value-Driven Decision-Making Process

The approach proposed in this paper aims at identifying the best solution in the design space while trading decision-makers' expectations with respect to criteria related to aircraft, manufacturing, and supply-chain systems. To ensure that criteria related to Enabling Systems are also accounted for in the early lifecycle stages of the System of Interest, stakeholders' needs related to the production of the aircraft are also collected early. From these needs, important criteria for decision-makers to value the systems are derived. The design space alternatives are then generated considering, at the same time, choices related to all systems. More details on the decision-making process formulation are provided in Section 2.1. In Section 2.2, the tools and technologies automatizing this methodology are introduced, in particular for VALORISE, the interactive dashboard supporting the multi-attribute decision-making process.

2.1. Methodology Formulation

To overcome the limits of the traditional sequential approach, in which decisions on supply and manufacturing are addressed once the operational performance of the aircraft is fixed (Figure 1a), this paper aims to include in the concept lifecycle stage operational requirements of the aircraft but also requirements related to the Enabling Systems (Figure 1b).

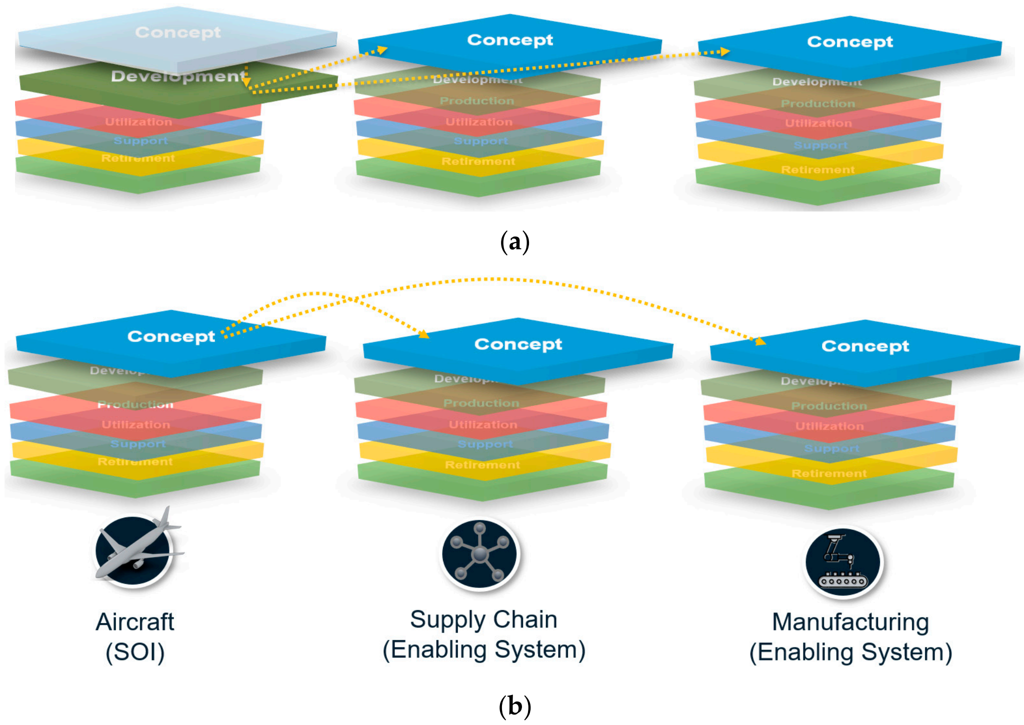


Figure 1. System of Interest (SoI) and Enabling Systems (ES) lifecycle stages: (**a**) Traditional sequential approach; (**b**) Proposed concurrent approach.

To achieve this objective, enterprises, engineers, and business managers are also involved as stakeholders to collect their needs and derive requirements related to aircraft, manufacturing, and supply-chain systems. At the same time, criteria identified by decision-makers as key to the value of the systems are also collected. Criteria for the identification of the best aircraft configuration are usually related to the operation of the system and, thus, to its performance (e.g., thrust, fuel consumption). More challenging is the identification of criteria related to aircraft production and, therefore, to the systems of supply chain and manufacturing because of their tacit nature. However, production risk, quality, and time are selected as criteria for the identification of the best supply chain because of the key role they have in supply-chain management [31]. These criteria, also known as supply-chain performance, are estimated considering transportation, manufacturing, and fixed contributions [32]. Since manufacturing contributions are included in the supply-chain performance, criteria related to manufacturing have not been explicitly considered for best-solution identification. A summary of the criteria is shown in Table 1. These criteria are used to identify the best solution among all the alternatives populating the design space.

Table 1. Criteria defined by decision-makers for best-solution identification.

System	Criteria
Supply Chain	Quality Risk Time
Aircraft	Operational Parameters

To generate the design space in which to select the best solution, several architectures are derived from the requirements, as shown in Figure 2. These architectures differ for the materials and processes of components, machines, and enterprises. Therefore, a huge number of architectures can be generated by making choices related to manufacturing, aircraft, and supply-chain systems. Once they are evaluated and optimized, these architectures represent the alternatives populating the design space.

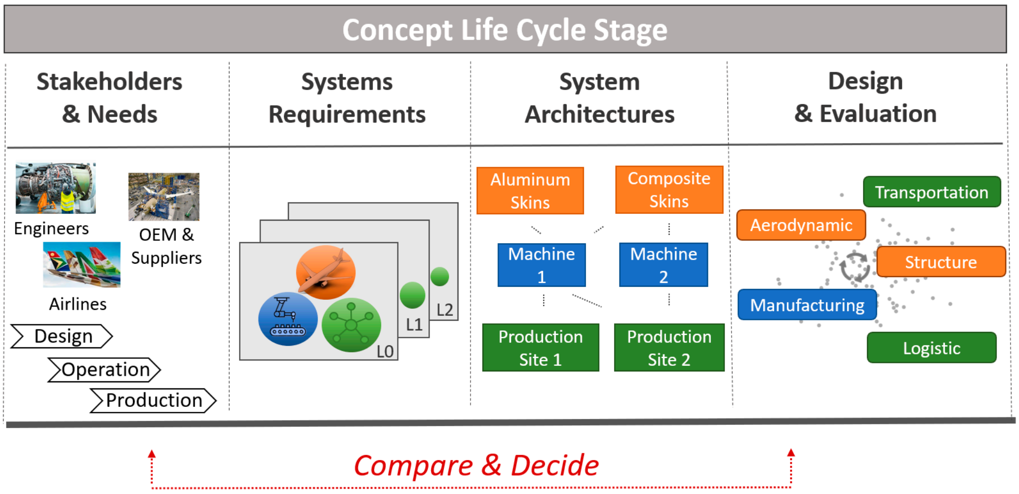


Figure 2. Methodology formulation: Identify the best solution in the design space by trading decision-makers' expectations with respect to criteria identified as key to value the manufacturing, aircraft, and supply-chain systems.

As the last step, the best alternative on the generated design space is identified, trading decision-makers' expectations with respect to criteria related to the manufacturing, supply chain, and aircraft systems. To identify the best solution while trading all the criteria reported in Table 2, Multi-Attribute Utility Theory is leveraged (see Appendix A). In fact, it is good practice to use MAUT when at least three criteria are considered for the decision-making process [33]. With this theory, all the criteria—also called attributes—are aggregated into one single dimensionless measure, i.e., value. In this way, the best solution, depending on multiple criteria, can be easily identified as the one with the highest value. To estimate the value, a weight and a utility function are assigned to each attribute. The weights represent the relative importance of each attribute. The single-attribute utility (SAU) functions, instead, are used to quantify decision-makers' expectations with respect to each attribute. SAU functions represent the way decision-makers would select a solution by only considering the specific attribute. In other words, they are used to translate the qualitative decision-makers' preferences into analytical curves.

Table 2. Decision-makers' expectations.

System	Attributes	Stakeholder's Expectation
Supply Chain	Quality	Higher the better
	Risk	Lower the better
	Time	Lower the better

The value-model theory allows decision-makers to explore several strategic scenarios by assigning attribute weights, thus prioritizing such attributes in different ways according to their needs. In addition, SAU functions support decision-makers by easily quantifying their expectations with respect to each criterion. Regarding this, several methods can be used to define utility functions; however, interactive tools in which decision-makers can directly design utility functions might support decision-makers in representing their qualitative preferences well [21]. VALORISE, the interactive dashboard introduced in the next subsection, has been developed in house for this reason.

In summary, once the key criteria for decision-makers to value the systems are defined, and the alternatives of the design space are evaluated, the value-model theory is used to easily identify the best solution in the value-driven trade space as the one with the highest value. This solution represents the best alternative for decision-makers with respect to operational and production aircraft requirements, i.e., value, and the aggregation of key criteria related to aircraft, manufacturing, and supply-chain systems.

An application case of this methodology is reported in Section 4. The tools and technologies used to implement such a methodology are introduced in the following subsection.

2.2. Methodology Implementation: VALORISE as a Value-Based Interactive Dashboard

The steps of the methodology shown in Figure 3 have been implemented in the AGILE 4.0 framework [34], extended, and applied to the aircraft, manufacturing, and supply-chain systems, as shown in Figure 3. Therefore, the tools and technologies of this framework allow the implementation of stakeholders' needs and requirements of three systems, the definition of criteria important for decision-makers, the creation of the system architectures, and the evaluation of them to generate the design space [35,36].

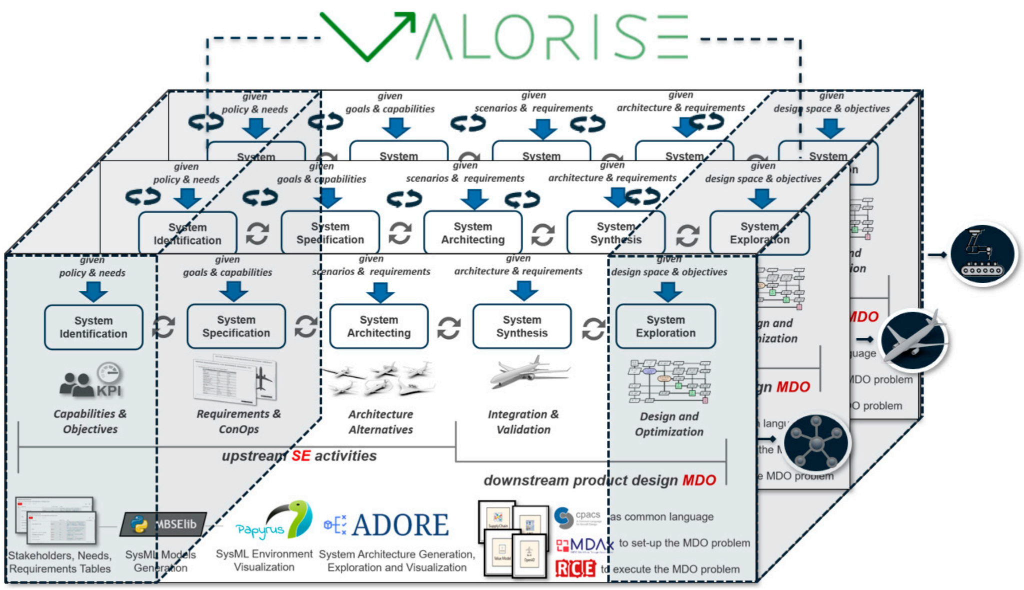


Figure 3. Methodology implementation—VALORISE to identify the best solution in the design space by trading decision-makers' expectations while considering the aircraft, manufacturing, and supply-chain systems.

By contrast, to identify the best solution in the design space (last step of the framework) by trading decision-makers' expectations with respect to the criteria identified as key to valuing the system (first step of the framework), VALORISE has been developed by the DLR.

VALORISE, which stands for **V**alue-driven tr**A**de-space visua**L**izati**O**n, explo**R**at**I**on, and a**S**s**E**ssment, is an interactive dashboard based on Multi-Attribute Utility Theory. It has been implemented to simplify and automatize the multi-criteria decision-making process, analyze real-time strategic scenarios, and easily explore the value-driven trade space for best-solution identification.

The inputs needed for VALORISE, collected in different file formats—among others, CPACS files [37]—are the specification of the criteria defined by decision-makers, e.g., the name and unit of measures, as well as the numerical estimation of such criteria for all the alternatives populating the design space. The settings of the value model, and, therefore, the assignment of weights and utility functions, can instead be defined by decision-makers directly in VALORISE, as shown in Figure 4.

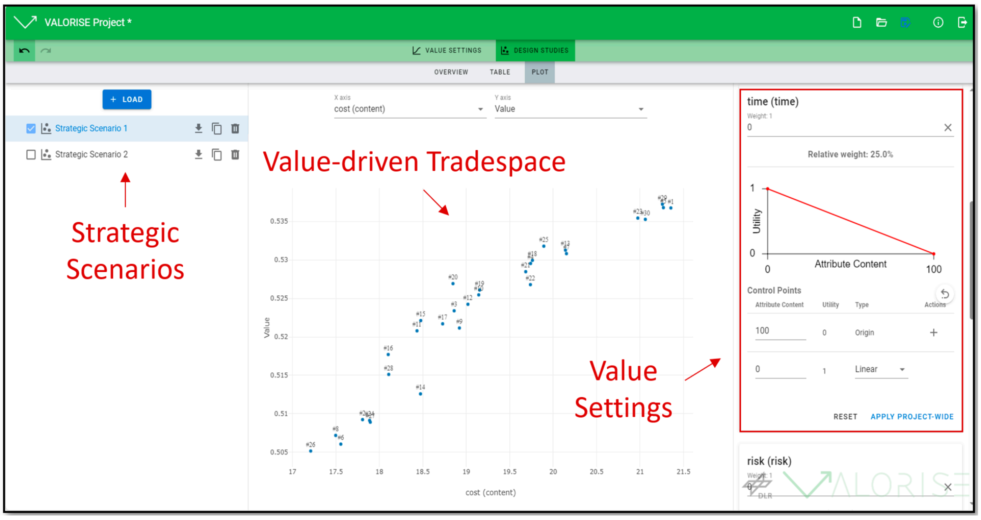


Figure 4. VALORISE as a value-driven interactive dashboard.

Decision-makers can interactively draw utility functions to represent their expectations with respect to each selected attribute and set several weight combinations to analyze the scenario of interest. Real-time scenarios can be investigated in VALORISE since changes in the attribute weights and/or utility functions (e.g., on the boundaries of contents) are directly visualized on the dashboard. This allows decision-makers to compare different scenarios before making strategic decisions. VALORISE also offers the possibility to export a table including the value and the attribute contents of each solution in a different format, if needed, for further analysis.

Finally, VALORISE can also be used as a stand-alone tool to be integrated into a toolchain with other tools. This integration is useful when, for instance, uncertainty propagation or sensitivity analysis on weights and utility functions must be performed for the identification of the robust solution. In this case, since a huge number of combinations must be explored, using VALORISE as a stand-alone tool instead of a dashboard reduces the computational time, as decision-makers do not have to set all the possible combinations manually.

In this research activity, however, VALORISE is used as a dashboard. Results related to an aeronautical application case leveraging VALORISE for the value-driven decision-making process are shown in the next section.

3. Aeronautical Case Study

The methodology described in Section 2, thus the identification of stakeholders' needs and requirements, the system architecture, and the design space exploration, have already been applied to an aeronautical case study [32,38]. In this paper, the focus is on the decision-making process and, in particular, on the identification of the best supply chain producing a specific aircraft component, namely the horizontal tail plane (HTP). The aim is to address decisions related to manufacturing and the supply chain in the early aircraft lifecycle stage to avoid increases in costs usually related to production issues. Attributes identified as key by decision-makers for the identification of the best supply chain were introduced in Section 2, Table 1. These are the production risk, quality, and time. To simplify the multi-attribute decision-making process, these criteria are aggregated into one single dimensionless measure, i.e., value, by assigning a weight and utility function to each of them. The best solution, trading decision-makers' expectations, can be easily identified in the value-driven trade space as the one with the highest value.

In Section 3.1, assumptions are introduced, leading to alternatives populating the design space on which to select the best solution. Then, the SAU functions provided by decision-makers are discussed. Based on these assumptions, in Section 3.2, the best supply chain in the value-driven trade-spaces is identified for each decision-maker. Two cases are presented: the first (Section 3.2.1) does not prioritize criteria; the second (Section 3.2.2) prioritizes time. The second case study is proposed as a proof of concept to show if and how the value-driven trade space changes when prioritizing attributes. Many other strategic scenarios can be further analyzed.

3.1. Application Case Setup

The baseline for the application case is the horizontal tail plane of a 90-passenger aircraft, mainly made of aluminum [39]. To simplify the problem and reduce the number of alternatives populating the design space, this HTP configuration is assumed to be fixed in terms of materials and process. The materials, manufacturing, and assembly processes characterizing the horizontal tail plane components are shown in Figure 5.

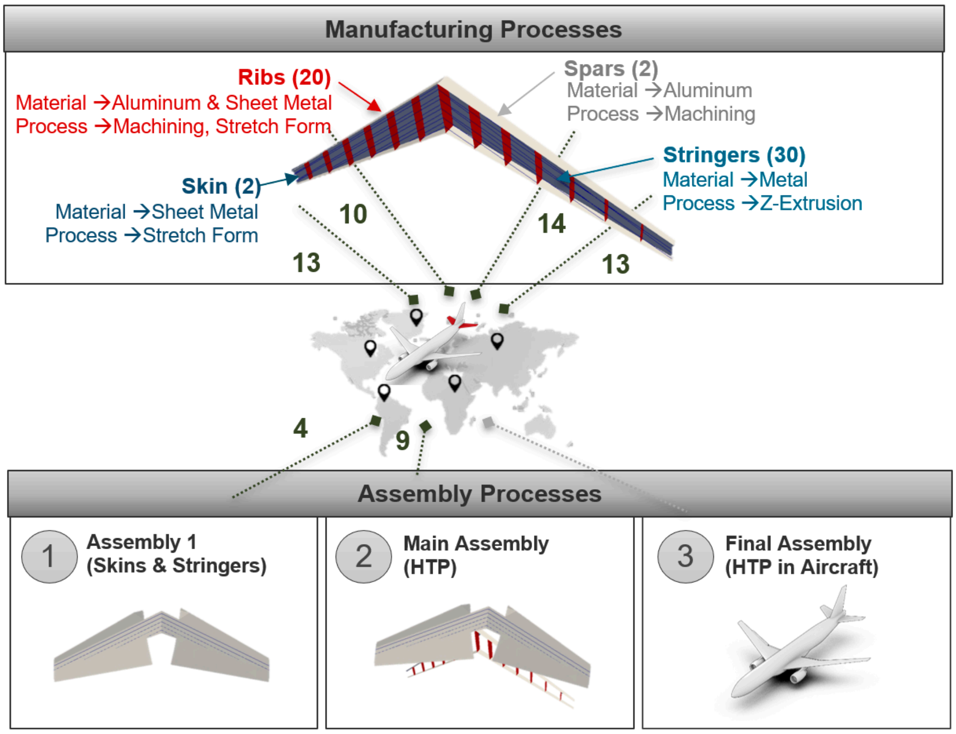


Figure 5. Design space assumptions: horizontal tail plane materials and processes; supply-chain alternatives as a combination of enterprises.

The alternatives populating the design space are generated considering the combinations of enterprises with the competencies to perform these selected materials and processes for each HTP component. Several enterprises can be selected for the manufacture of such components, as shown in Figure 5 (upper panel). For the assembly processes, by contrast, several enterprises can be selected for each assembly process, as shown in Figure 5 (lower panel). In particular, 4 enterprises can be selected for Assembly 1, in which skins and stringers are joined together, and 9 enterprises can be selected for the Main Assembly, in which the joined skins and stringers are combined with the joined spars and ribs. Instead, the Final Assembly of installing the HTP into the rest of the aircraft is the only process assumed to be performed by a single enterprise. The qualitative decision-makers' expectations are summarized in Table 2. As expected, decision-makers prefer supply chains with low production time and risk and high quality.

The enterprises involved in the manufacture and assembly of the HTP components are spread all around the world, and are in-house sites and suppliers. Therefore, depending on the combined enterprises, production scenarios are analyzed in which the HTP components are fully made in house, fully outsourced to suppliers, or partially made in house and partially outsourced. The full enumeration of alternatives is 9×10^6. However, only 19 supply-chain alternatives are identified on the 4-objective Pareto front [39–41]. These solutions are the optimum supply chains in terms of production performance. The aim of this application case is to identify the best supply chain among these 19 optimized alternatives while considering, at the same time, decision-makers' expectations with respect to production risk, time, and quality. Therefore, as the next step, the decision-makers' expectations must be defined.

To estimate the value of the 19 alternatives, these qualitative expectations have to be translated into analytical functions that are the single-attribute utility functions. The utility functions drawn by decision-makers in VALORISE are reported in Figure 6. These utility functions, shown in Figure 6, have been provided by the two industrial partners involved in this research activity within the European Project AGILE4.0, here called Decision-Maker A and Decision-Maker B. The qualitative preferences are the same for both decision-makers (Table 2). By contrast, the quantification through utility functions of those expectations changes with respect to each decision-maker (Figure 6b,c). A different utility is associated with each attribute by each decision-maker, depending on the way they make decisions. For example, referring to the time utility functions, Decision-Maker A's willingness to accept a solution with low production time is lower than that of Decision-Maker B, as shown by the yellow stars in Figure 6b,c. As a consequence, the same solution (supply chain) has a different value based on the utility associated with attributes by decision-makers. The utility function implementation, therefore, allows the consideration of decision-makers' expectations in the design space.

Linear utility functions, in the first row of Figure 6, are included in the case study since they are used to create a reference value-driven trade space uninfluenced by decision-makers. Attribute contents are normalized (0 to 100) due to the intellectual properties of the industrial partners involved in the application case. In the case of linear functions, utilities do not represent decision-maker preferences, but they can be read as analytical functions that can be used to translate different parameters with different scales of measurement in the same dimensionless ones for correct comparison. In this case, the solution with the highest value might not be the best solution for decision-makers since decision-maker expectations have not been considered yet.

Once the utility functions are defined, a weight must be assigned to each attribute to estimate the value of the 19 alternatives and identify the best solution. In the next subsection, the best supply chain for decision-makers is identified when the same weight is assigned to all the attributes (no prioritization) or when one of them (time) is prioritized.

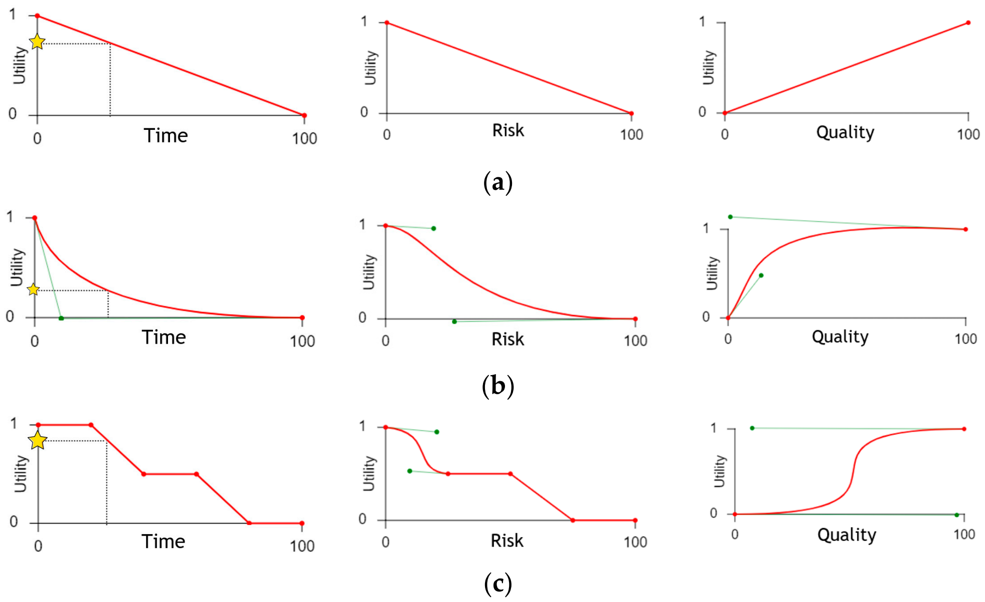


Figure 6. Single-attribute utility functions quantifying decision-makers' expectations drawn in VALORISE (**a**) Reference Case (**b**) Decision-Maker A (**c**) Decision-Maker B.

3.2. Results: Value-Driven Trade-Space Exploration

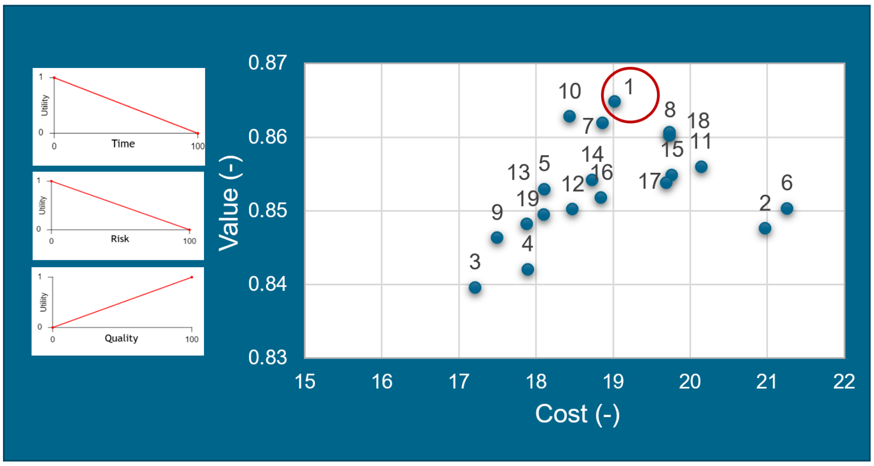
Here, the value-driven trade-spaces are presented, implementing decision-makers' expectations through the utility functions introduced in the previous section. Two case studies are addressed. In the first, attributes are not prioritized, meaning that the same weight is assigned to all the attributes. In the second, one of the attributes (time) is prioritized. As already mentioned, this case study is proposed as a proof of concept to show if and how the value-driven trade-spaces change when prioritizing attributes. Many other strategic scenarios can be further analyzed.

3.2.1. Case Study without Attribute Prioritization

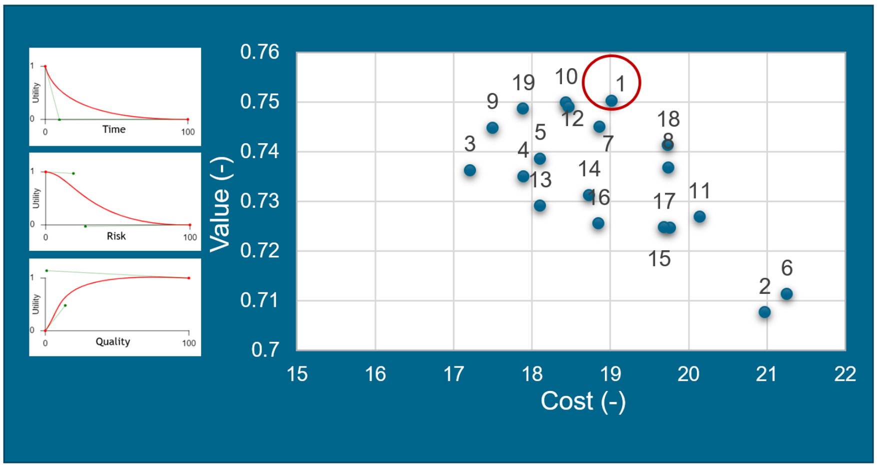
The value-driven trade-spaces generated by implementing the utility functions reported in Figure 6, and assuming the same weights for all the attributes, are reported in Figure 7. In this case, there is no attribute prioritization since the same weight (0.33) is assigned to all the attributes. Instead, decision-makers' expectations are accounted for in the design space through the utility functions.

The solution with the highest value highlighted in the reference case is the best analytical solution since decision-makers' expectations are not implemented, as explained in Section 3.1. This solution turns out to be the best one for Decision-Maker A but not for Decision-Maker B. Implementing utility functions is, therefore, essential for the identification of the best solution that matches the decision-makers' expectations. Indeed, the best solution for Decision-Makers A and B, i.e., the one with the highest value in the value-driven trade-spaces, is different, being, respectively, Solutions 1 and 10, as highlighted by the red circles in Figure 7b,c. The reason for this lies in the different utilities that decision-makers assign to attributes and, thus, to the different ways of making decisions. These best solutions correspond to supply chains matching decision-makers' expectations in terms of risk, time, and quality since these are the attributes aggregated in value.

In detail, the two best solutions (1 and 10) correspond to the same supply chain, thus to the same combination of enterprises. However, these enterprises perform different manufacturing and/or assembly processes. In this specific case, as shown in Table 3, the only difference between the two supply chain relays in the in-house site responsible for the Main Assembly is, respectively, In-House Site 1 for Supply Chain 1 and In-House Site 2 for Supply Chain 10. The percentage of ribs specified in Table 3 represents the amount of ribs produced by each single enterprise. For the other components (skins, spars, and stringers), it is assumed that each enterprise is responsible for the manufacture of all of them. The number of components, materials, and processes characterizing the HTP components (skins, stringers, spars, and ribs) were introduced in Figure 5.



(**a**)



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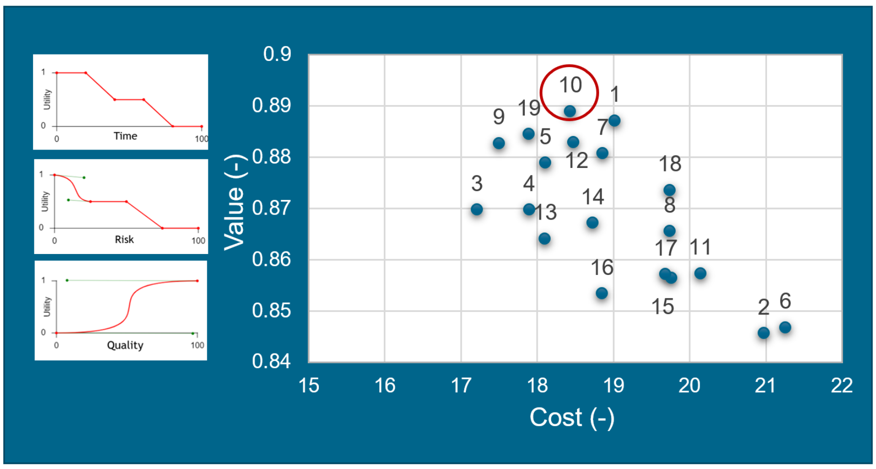


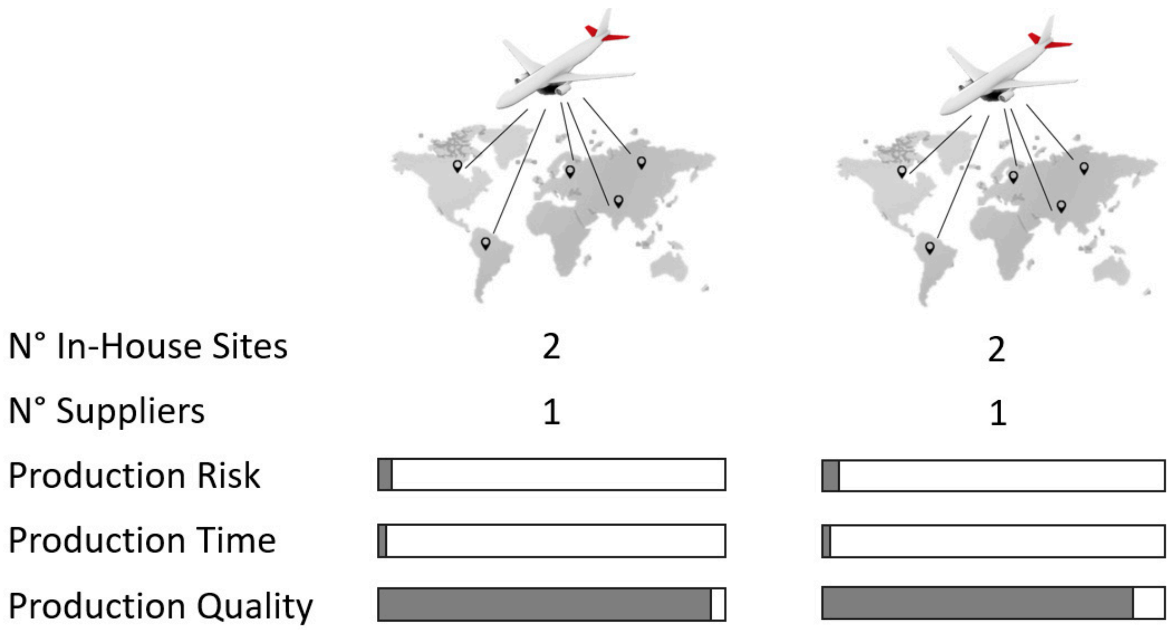
(**c**)

Figure 7. Value-driven trade space without attribute prioritization: (**a**) Reference case; (**b**) Decision-Maker A; (**c**) Decision-Maker B.

Table 3. Manufacturing and assembly processes are performed by the enterprises involved in the best supply chains for Decision-Maker A—Solution 1 (X) and Decision-Maker B—Solution 10 (-).

	Skin	**Ribs**		**Spars**	**Stringers**	**Assembly1**	**Main Assembly**
		30%	**70%**				
In-House Site 1				X -		X -	X
In-House Site 2	X -	X -			X -		-
Supplier 1			X -				

The difference in the enterprise performing the Main Assembly leads to different production risks, time, and quality (and thus value). As shown in Figure 8, the production performance of these supply chains is almost the same, except for the quality. This is mainly related to the different competencies that the two in-house sites have in performing the Main Assembly. The difference in production risk and time is related to competencies but also to transportation contribution, with the two sites located in two different geographic locations. However, this difference and, in general, the difference in the production performance of Supply Chain 1 and 10 is very slight. This is also because the 19 solutions of the value-driven trade-spaces are all optimized solutions.



(a) (b)

Figure 8. Production performance of best supply chains: (**a**) Solution 1 for Decision-Maker A (**b**) Solution 10 for Decision-Maker B.

The slight difference in the production performance of Supply Chain 1 and 10 implies a small difference in the value of these two alternatives. Nevertheless, Supply Chain 10 has a relatively lower cost than Supply Chain 10. The motivations still rely on the competencies of the enterprises, and thus on the manufacturing cost, as well as in the geographic location in which enterprises are located that lead to different fixed and transportation costs. In both cases, however, the costs related to Supply Chain 1 and 10 are high compared with other solutions, e.g., solution 3. This solution has a lower cost but also value. Value vs. cost tradeoff studies can be performed by exploring the value-driven trade space. An example of a solution investigation of interest for Decision-Maker A is reported in Figure 9. The same discussion can be addressed for Decision-Maker B.

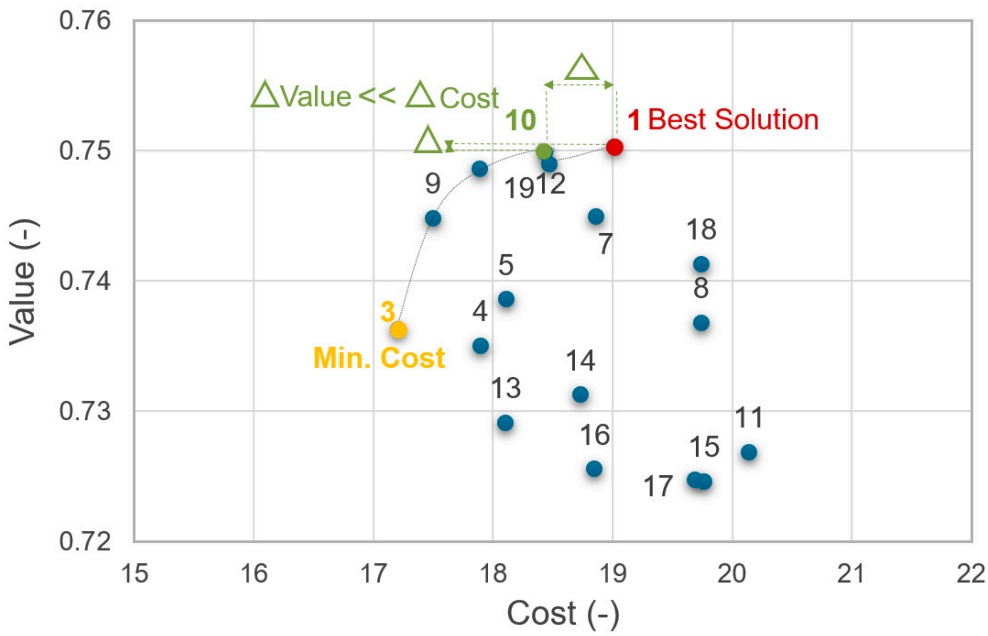


Figure 9. Value-driven trade-space exploration for Decision-Maker A: "Value vs. Cost" and "Make or Buy" tradeoff studies.

The solutions highlighted in Figure 9 are Solutions 1 and 10, which have already been introduced, and Solution 3. Looking at the value-driven Pareto front (the dashed line in Figure 9), these solutions might be of interest to Decision-Maker A because they, respectively, represent:

- Solution 1: the best solution with the highest value and cost
- Solution 10: a solution with high value but reduced cost
- Solution 3: the solution with minimum value and cost

Solutions 1 and 10 have already been introduced. These solutions represent the same supply chain in which most of the processes are performed at in-house sites, and the only difference is in the enterprise performing the Main Assembly. In Supply Chain 3, two other enterprises are involved: another in-house site and a supplier. A summary of the processes performed by each supply chain (1,10,3) is reported in Table 4.

Table 4. Manufacturing and assembly processes performed by the enterprises involved in the supply chain with lowest value and cost—Solution 3 (#) compared with best supply chains for Decision-Maker A—Solution 1 (X)—and Decision-Maker B—Solution 10 (-).

	Skin	Ribs		Spars	Stringers	Assembly1	Main Assembly
		30%	70%				
In-House Site 1				X - #		X - #	X
In-House Site 2	X -	X -			X -		- #
In-House Site 3	#	#					
Supplier 1			X - #				
Supplier 2					#		

The production performance of Supply Chain 3 is instead reported in Figure 10. This supply chain has a higher production risk and time and a lower quality if compared to Supply Chains 1 and 10. This is, once again, mainly related to the competencies of the enterprises involved. In this specific case, however, the manufacturing of stringers is also outsourced to suppliers. In addition, the cost associated with this supply chain is lower than those of Supply Chains 1 and 10. The motivation relies on the competencies of enterprises since low competencies lead to low cost, but also to transportation. In fact, in Supply Chain 3, most of the components are transported by water, which reduces the transportation cost but increases the risk and time with a consequent decrease in value.

Figure 10. Production performance of Supply Chain 3 characterized by the lowest cost and value.

With this approach, decision-makers can, therefore, decide, from the early aircraft lifecycle stage, whether to select a solution with lower risk and time and higher quality (so high value), therefore investing more cost, or pay less, therefore selecting a riskier supply chain. In addition, decision-makers can also address the "make or buy" tradeoff by deciding whether to produce mostly in house, paying more but having higher value (Solution 1 and 10), or rely more on suppliers, which can be risky (low value) but less expensive (Solution 3).

3.2.2. Case Study with Time Prioritization

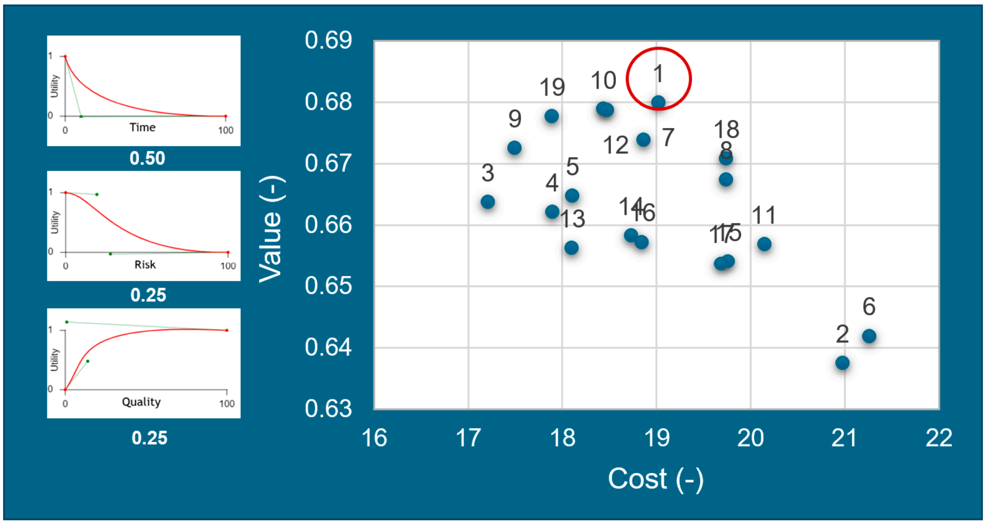
In the previous case study, the best solution for the value-driven trade-spaces was identified by assuming the same weights for all the attributes. This assumption implies that there is no prioritization among attributes, and, as a consequence, the value-driven trade space is influenced only by decision-makers' expectations implemented in utility functions. However, strategic scenarios can be analyzed by prioritizing attributes, therefore assigning different weight combinations to attributes. This can be easily done in VALORISE since it gives decision-makers the possibility to check the value-driven trade-space changes in real time based on the weight combination analyzed. As a proof of concept, an example of value-driven trade-space exploration, when time is prioritized with respect to the other attributes, is addressed in this case study to show how and if the value-driven trade-space changes.

The weight combination analyzed is reported in Table 5, where, by contrast, the utility functions are the same as those plotted in Figure 6. The aim of this application case is to identify the best supply chain producing the specific HTP configuration (Figure 5) in a scenario in which production time plays a key role for decision-makers.

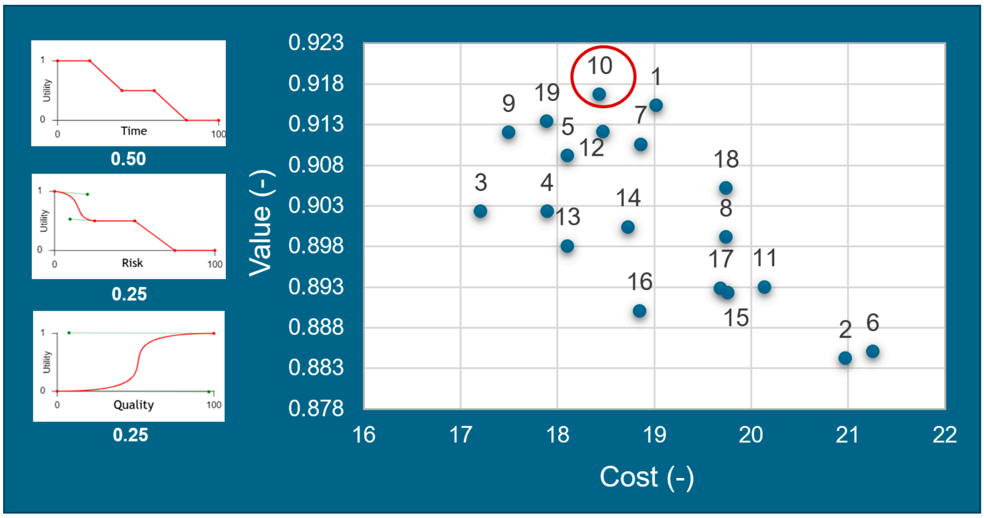
Table 5. Weight combination: time prioritization.

Attribute	Weight
Risk	0.25
Time	0.50
Quality	0.25

The value-driven trade-spaces of this case study, called time prioritization, are shown in Figure 11 for both decision-makers. In this specific case, the best solutions for Decision-Makers A and B are still, respectively, Supply Chain 1 and Solution 10. However, the value associated with these solutions drastically changes because of the higher weight associated with time.



(**a**)



(**b**)

Figure 11. Value-driven trade-spaces for the time prioritization case study: (**a**) Decision-Maker A; (**b**) Decision-Maker B.

Therefore, for this specific case, the best solutions remain the same for both decision-makers even if the value associated with these solutions changes because of time prioritization. Exploring several weight combinations, it is possible to identify the best solution, i.e., the solution with the highest value, but also the most robust solution, i.e., the solution whose variation in value does not drastically change in the different strategic scenarios. Decision-makers can perform other interesting tradeoff studies and decide whenever to select the best solution for specific scenarios or the robust solution whose oscillation in value is not so high in all the strategic scenarios of interest.

4. Implications and Findings

A value-driven concurrent approach addressing decisions considering aircraft, manufacturing, and supply-chain criteria at the same time is proposed in this paper. The objective is to overcome the limits of the sequential approach, traditionally adopted by aeronautical companies, in which decisions about supply chain and manufacture are addressed once the aeronautical system configuration is fixed after decisions about the aircraft configuration have already been addressed.

The challenge faced in this research activity is to formalize, automatize, and simplify multi-criteria decision-making processes when the aircraft, i.e., the System of Interest, and the manufacturing and supply-chain systems, defined as Enabling Systems, are designed at the same time, i.e., when decisions on the three systems are concurrently addressed in the concept stage. To perform the multi-criteria decision-making process, decision-makers' criteria related to both the operation and production are collected. The design space is then generated considering choices related to the aircraft (e.g., number of components), to the manufacturing (e.g., materials and processes), and to the supply chain (e.g., enterprises). Then, value-model theory is adopted to simplify the multi-criteria decision-making process, thus identifying the best solution in the design space while trading decision-makers' expectations with respect to criteria related to multiple systems. This allows decision-makers to also consider, from the early lifecycle stages, "-ilities", which usually represent hidden sources of increasing cost.

The value model adopted in this study is the Multi-Attribute Utility Theory. It is not the aim of this paper to develop a new value-model theory. Instead, the idea is to apply already existing value-model theories to new application cases and, in this case, to extend the criteria important for making decisions to aircraft production (manufacturing and supply chain). Therefore, MAUT has been applied to the design, manufacturing, and supply chain of a specific aircraft component, i.e., the horizontal tail plane. This proved to be useful for the identification of the best solution when the aircraft, manufacturing, and supply-chain systems were considered. The best solution based on multiple criteria can be then easily identified as that with the highest value. Other value-model theories might be explored in future studies and implemented in VALORISE.

VALORISE is an in-house value-based dashboard developed to support and automatize the multi-criteria decision-making process. It is used to automatize the decision-making process and easily identify the best solution on the Pareto front by trading multiple decision-makers' expectations. VALORISE supports decision-makers in modeling their expectations, analyzing real-time strategic scenarios by prioritizing criteria, and easily exploring the value-driven trade space for best-solution identification. Having a tool supporting decision-makers in the elicitation of the utility functions is key when applying the value-model theory. With VALORISE, decision-makers could easily draw their own utility functions and explore scenarios of interest by themselves, easily changing the weights associated with attributes. This allows decision-makers to perform uncertainty propagation analysis and, therefore, identify the most robust solution, i.e., the alternative whose value is almost constant in all the strategic scenarios of interest. Decision-makers can decide whether to select the best solution for a specific strategic scenario or the robust solution with a lower value in a specific scenario but whose oscillation in value is relatively small in all the strategic scenarios [7,42].

Finally, the application case demonstrates the possibility of performing "value vs. cost" and thus "make or buy" tradeoff studies, giving decision-makers the opportunity to decide whether to produce in house (high value, high cost) or outsource to suppliers (low value, low cost). The final decision in this paper always falls on decision-makers as requested by industrial partners. As the first study, a trade space in which several alternatives can be explored and analyzed is preferred over having only one solution selected as the best by applying artificial intelligence algorithms.

5. Conclusions

A concurrent value-driven approach is proposed in this research activity. The objective is to address decisions on the aircraft, supply chain, and manufacturing at the same time. The formalization of the proposition and details on the tools and technologies used to automatize it are reported in Section 2. The focus is especially on VALORISE, the value-based interactive dashboard developed at the DLR, supporting decision-makers in easily modeling their expectations through utility functions, analyzing real-time strategic scenarios by prioritizing criteria, and exploring the value-driven trade-spaces for best-solution identification. VALORISE was used by decision-makers to model their own utility functions for the case study reported in Section 3. Results show that by leveraging this approach, enterprises can perform "value vs. cost" or "make vs. buy" tradeoff studies. This approach, therefore, provides decision-makers with the opportunity to consider, from the early lifecycle stages, the "-ilities" related to production, usually representing hidden sources of increase in cost.

Activities already in progress aim to complexify the application case, including the variability of materials and processes and, thus, the HTP configuration for the identification of the best supply chain for the best HTP configuration. From a decision-making perspective, the process is the same, with the only difference being the reliance on the number of aggregated criteria. The challenge is more on the elicitation of the Pareto front, depending on the optimization algorithms used.

As further studies, uncertainty propagation or sensitivity analysis on weights and utility functions are recommended for the identification of robust solutions. In addition, other value-model theories can be explored for study completeness.

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Appendix A

Several techniques can be used to support decision-makers in formalizing their value structure. In this approach, the Multi-Attribute Utility (MAU) value model is used (Ross, Rhodes, & Fitzgerald, 2005 [21]; Keeney & Howard, 1993 [43]):

$$\text{value} = \sum_{i=1}^{N} \lambda_i \, U(X_i) \tag{A1}$$

In which:

- N is the number of attributes;
- $U\,(X_i)$ is the single-attribute utility function;
- λ_i is the weight associated with attributes X_i:

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